LEGUME ABUNDANCE IN NEW ZEALAND SUMMER-MOIST AND SUMMER-DRY HILL COUNTRY PASTURES

A thesis presented in partial fulfilment of the requirements of the degree of

*Doctor of Philosophy (PhD)*

Institute of Natural Resources
Massey University
Palmerston North, New Zealand

Christian Hepp
2003
To Paulina, for her love, patience and constant support
To Nicolas, Benjamin, Vicente and 'Chumi', my dear boys
To my dear father who inspired me
To my mother for her unconditional love

... 'Immer wenn Du meinst, es geht nicht mehr, kommt von irgendwo ein Lichtlein her...’
The introduction of legumes has been a central factor in hill country pasture improvement in New Zealand since they are able to fix atmospheric nitrogen to contribute to pasture production and also improve pasture quality. However, at present legume content of hill swards has dropped to generally very low levels which will likely affect medium-long term sustainability of these pastoral ecosystems. This thesis is focussed on determining the relative importance of management and environmental factors that affect legume abundance in hill country swards. A series of field experiments were undertaken between May 2000 and April 2002 in contrasting summer-moist (Ballantrae; 40°19'S, 175°50'E) and summer-dry (Waipawa; 40°00'S, 176°23'E) hill country areas, including north aspects and south aspects at Waipawa, to evaluate the relative impacts of cutting height (targets of 3 or 7 cm), grass suppression by application of selective herbicide, soil-P status (high or low), autumn nitrogen application (0 or 50 kg N/ha), defoliation management (cutting, and rotational grazing with sheep), on legume abundance. A glasshouse experiment involved the effects of companion grasses and defoliation on individual white clover and subterranean clover plants grown in pots.

The suppression of grass competition caused the most marked changes in short-term sward composition, with an increase in legume abundance at all sites. Increasing soil-P status increased legume abundance, especially where white clover was present as a major botanical component. Altering pasture cutting height or applying nitrogen in the autumn had comparatively minor effects on legume abundance. Defoliation management (i.e. rotational grazing with sheep compared with cutting) played a secondary role in affecting legume abundance of swards, at least in the short term.
Residual effects of grass suppression resulted in an increase in legume abundance, which persisted for at least one year after treatment and affected legume species composition in the drier Waipawa north aspect. Pastures in the summer-moist areas showed a high degree of resilience and reverted quickly to the original grass dominance. Inter-annual and site contrasts in soil moisture patterns highlighted the relevance of soil moisture as a key factor in determining legume abundance and production, mainly in the summer-dry areas. In the glasshouse trial, severe defoliation had very strong effects, reducing plant size, leaf area, vegetative stem development and branching of individual legume plants. Moreover, root competition from grasses was seen to significantly limit clover shoot growth, this being more important than the shading effect.

From these experiments, it is suggested that the relative importance of factors affecting legume abundance in hill pastures is: soil moisture (if limiting, e.g. summer-dry hill country) > grass suppression > soil-P status > defoliation management > nitrogen application. However, some of these factors have been noted to interact, and relationships can acquire higher levels of complexity.

This study highlighted the relative importance of factors that influence legume abundance of hill country swards and showed that pasture composition can be dramatically modified and legume content increased, but also that these changes can be short-lived. Summer-dry hill country pastures strongly rely on highly variable non-manageable seasonal and inter-annual soil moisture profiles, and legume abundance is difficult to predict and less stable in time than in summer-moist conditions. However, a high potential of legume abundance is achievable with adequate soil moisture in summer, even at low soil-P status. In these dryland areas, the combination of limiting soil moisture, close-to-ground defoliation, and selective grazing, is likely to severely limit white clover growth and spread, and be aggravated by low soil-P status, as well as subterranean clover growth and seed set, therefore compromising legume abundance in the following season.
High tiller population density, combined with a high frequency and intensity of legume defoliation, will put legumes under stress from severe grass competition, ultimately affecting legume abundance. This is likely to be the case for many intensively set stocked hill country systems managed with sheep.

**Keywords:** Hill country pastures, legume abundance, white clover, subterranean clover, soil moisture, summer-dry, summer-moist, grass suppression, competition, cutting, rotational grazing, soil phosphorus status, nitrogen fertiliser.
ACKNOWLEDGEMENTS

I am deeply grateful to Professor John Hodgson (Institute of Natural Resources INR, Massey University) for his most generous support from our very first contacts from Chile to the completion of this degree. Prof's co-supervision, guidance, enthusiasm, encouragement, kindness, and permanent interest in my work, have been vital to me, and I am permanently indebted for it. I am still amazed at how fast and thorough he could speed through endless drafts of the thesis.

I would like to express my gratitude to Dr. Ian Valentine, Dr. Peter Kemp (INR, Massey University) and Dr. Allan Gillingham (Agresearch Grasslands) for their supervision, guidance and encouragement at different stages of the work, and especially through the process of revision of different versions and drafts of this thesis. Their advice, comments, support, friendly approach and help have made this work more motivating and fruitful.

Special thanks to Dr. Kerry Harrington (INR) for advice and help on herbicide use, Dr. Cory Matthew (INR) for setting up the root-washing facility, Dr. Alec Mackay (Agresearch) for support in the initial planning of the project, and Duncan Hedderley for statistical advice and his patience in responding my periodic enquiries.

Many thanks to a large group of people that helped at different stages of the experimental work: Mark Osborne, who provided much of the necessary gear and supplies, Bob Toes for his friendly help and teachings in the soil lab, Ian Furkert for pressure plate determinations and Ross Wallace for help with root washing. Brian Devantier (Agresearch) helped at the set-up stage and Phillip Budding with moisture sample processing at Ballantrae; Maurice Gray and Stuart Macmillan (Agresearch) cooperated with management of the experiments at the Waipawa site. Lindsay Sylva, Lesley Taylor and Ben Anderson (Plant Growth Unit, Massey) helped with the set-up
and management of the glasshouse experiment. Yvonne Gray, Hera Kennedy, Irene Manley, Pam Howell and Ruwan Dissayanake also helped and supported in different ways. A huge thank you to you all. Special thanks to my friend Roger Levy, who helped me in the set-up of experiments and with several sampling procedures. His skilled help, very special sense of humour, extensive communication skills and optimism made the difference in those long days of sampling in the otherwise lone and steep hills.

Sarah Hurst (Hortresearch), Elaine Fouhy (NZ MetService) and NIWA kindly provided climatic data, which is thankfully acknowledged. Dean Richards and Kevin Harris helped with all computing related support, and their assistance is deeply appreciated. Silvia Hooker and Dianne Reilly from the International Students Office offered permanent friendly support for which I am very grateful.

A special thank you to Bill Gates and Microsoft Inc. for its amazing creation, the ‘Word’ program. Only through a document of this magnitude have I been able to explore some of the endless possibilities of this instrument, which usually makes life so much easier.

The financial assistance of Instituto de Investigaciones Agropecuarias (INIA-Chile), that supported our family through a scholarship during our stay in New Zealand, is gratefully acknowledged. The help received through the Pastoral Science Scholarship (Massey University) is also thankfully recognised.

During my stay at Massey University I met many fellow students, some of whom became true friends and provided a highly diversified and pleasant working environment. Thanks to Walter Ayala, Juan Cañumir, Tara Pande, Andrew Wall, Jorge Zegbe, Dora Duarte de Carvallo, Wagner Beskow, Jose Rossi, Alvaro Romera, Alfredo Jimenez, Patricia Salles, Melissa Ercolin, Ignacio Lopez, Carlos Hug, Karin Timcke, Alejandra, Ignacio Donoso, Anita Kunz, and ‘little’ Sumanasena. Your friendship and support will not be forgotten.
We have spent wonderful moments in New Zealand, and we certainly will leave part of our hearts in this beautiful Island when we return to our Patagonian home. It was an extraordinary experience for our family to live three years in this amazing country in which we have learned to love the ‘kiwi’ approach and way of life. Thanks to many kiwi friends (an ‘amazing race’ of people) that have helped us in many ways and areas of daily life. The support of friends was vital to be able to go through difficult and sad moments, but it was wonderful to share the good and happy moments too. Special thanks to Patty and Juan, Roger and Paula, and Cornelia, amongst others.

A special thank you to my parents, whose love and support has been endless through many stages of my life. To my dear father, whom I embraced three years ago without realising that I would not embrace him again; I will never forget you.

Finally, my deepest and very special gratitude goes to my dear wife Paulina. Her willingness to embark in this ‘crazy’ and uncertain venture of crossing the Pacific Ocean for three years with a load of four boys aged between 1 and 10 is still a dilemma for me. It has been a hard time for her, but I have felt her love, support and commitment throughout this difficult time. Her help in the glasshouse and endless botanical separations is also ‘endlessly’ appreciated. Our sons Nicolas and Benjamin helped also at different stages of the experiments, while Vicente and Christian (‘Chumi’) have cheered me up and kept me going. Without the love and support of my family, I would not have been able to go through all this process.

Christian

Palmerston North, March 2003.
TABLE OF CONTENTS

ABSTRACT .................................................................................................................. I
ACKNOWLEDGEMENTS .............................................................................................. IV
TABLE OF CONTENTS ............................................................................................... VII
LIST OF TABLES .......................................................................................................... XI
LIST OF FIGURES ........................................................................................................ XX
LIST OF PLATES .......................................................................................................... XXIII

CHAPTER 1 ................................................................................................................ 1
GENERAL INTRODUCTION ......................................................................................... 1

1.1 INTRODUCTION .................................................................................................. 2
1.2 OBJECTIVES ....................................................................................................... 4
1.3 THESIS OUTLINE ............................................................................................... 5
  1.3.1. Chapter 2 ..................................................................................................... 5
  1.3.2. Chapter 3 ..................................................................................................... 5
  1.3.3. Chapter 4 ..................................................................................................... 6
  1.3.4. Chapter 5 ..................................................................................................... 6
  1.3.5. Chapter 6 ..................................................................................................... 6

CHAPTER 2 ................................................................................................................ 7
LITERATURE REVIEW ................................................................................................. 7

2.1 RELEVANCE OF LEGUMES IN NEW ZEALAND HILL COUNTRY .......... 7
  2.1.1. Pasture development in hill country ............................................................. 7
  2.1.2. Hill country contrasts ................................................................................ 9
  2.1.3. Legume species in hill country .................................................................. 11
  2.1.4. Legume establishment in hill country ......................................................... 19
2.2 FACTORS LIMITING LEGUME ABUNDANCE IN HILL COUNTRY ....... 21
  2.2.1. Climatic factors ......................................................................................... 21
  2.2.2. Soil fertility ............................................................................................... 25
  2.2.3. Competition .............................................................................................. 33
  2.2.4. Pasture utilization .................................................................................... 41
  2.2.5. Genotype ................................................................................................ 53
  2.2.6. Pests and diseases .................................................................................... 55
2.3 CONCLUSIONS .................................................................................................. 56
TABLE OF CONTENTS

CHAPTER 3 ........................................................................................................... 59
INFLUENCE OF MANAGEMENT AND ENVIRONMENTAL EFFECTS ON LEGUME ABUNDANCE UNDER CUTTING CONDITIONS AT CONTRASTING HILL COUNTRY PASTURE SITES ........................................... 59

3.1  INTRODUCTION ............................................................................................. 59
3.2  MATERIALS AND METHODS ......................................................................... 60
  3.2.1  Sites ........................................................................................................... 60
  3.2.2  Previous management .............................................................................. 61
  3.2.3  Design and treatments ............................................................................ 62
  3.2.4  Measurements .......................................................................................... 65
  3.2.5  Statistical analysis .................................................................................... 66
3.3  RESULTS ......................................................................................................... 67
  3.3.1  General results layout .............................................................................. 67
  3.3.2  Waipawa north aspect ............................................................................. 67
  3.3.3  Waipawa south aspect ............................................................................ 89
  3.3.4  Ballantrae .................................................................................................. 109
3.4  DISCUSSION .................................................................................................. 129
  3.4.1  Grass suppression .................................................................................... 129
  3.4.2  Soil-P status ............................................................................................. 135
  3.4.3  Cutting height .......................................................................................... 136
  3.4.4  Nitrogen application ............................................................................... 136
3.5  CONCLUSIONS ................................................................................................. 138

CHAPTER 4 ........................................................................................................... 139
EFFECTS OF GRAZING AND GRASS SUPPRESSION ON LEGUME ABUNDANCE AND PRODUCTION UNDER HIGH AND LOW SOIL-P LEVELS IN SUMMER-MOIST AND SUMMER-DRY HILL COUNTRY ....... 139

4.1  INTRODUCTION ............................................................................................. 139
4.2  MATERIALS AND METHODS ......................................................................... 140
  4.2.1  Sites ........................................................................................................... 140
  4.2.2  Design and treatments ............................................................................ 140
  4.2.3  Measurements .......................................................................................... 142
  4.2.4  Statistical analysis .................................................................................... 144
4.3  RESULTS ......................................................................................................... 145
  4.3.1  General results layout .............................................................................. 145
  4.3.2  Waipawa .................................................................................................... 145
  4.3.3  Ballantrae .................................................................................................. 192
4.4  DISCUSSION .................................................................................................. 227
  4.4.1  Year effects on summer-dry hill country pastures .................................. 227
  4.4.2  Magnitude of treatment effects ................................................................. 228
  4.4.3  Management regime ............................................................................... 229
### TABLE OF CONTENTS

4.4.4. Grass suppression .......................................................... 232
4.4.5. Soil-P status ............................................................... 238
4.5 CONCLUSIONS ................................................................. 239

CHAPTER 5 .................................................................................. 241

EFFECTS OF COMPANION GRASS STRUCTURE ON INDIVIDUAL WHITE CLOVER AND SUBTERRANEAN CLOVER PLANTS WITH TWO DEFOLIATION REGIMES UNDER GLASSHOUSE CONDITIONS .......... 241

5.1 INTRODUCTION ................................................................. 241
5.2 MATERIALS AND METHODS .................................................. 242
5.2.1. General .................................................................. 242
5.2.2. Design and treatments .................................................. 242
5.2.3. Measurements ............................................................. 246
5.2.4. Statistical analysis ......................................................... 248
5.3 RESULTS ............................................................................. 249
5.3.1. General results layout .................................................... 249
5.3.2. Glasshouse environment ................................................. 250
5.3.3. Initial grass and legume measurements ......................... 251
5.3.4. Effect of legume species ................................................ 252
5.3.5. Effect of companion grass structure .............................. 255
5.3.6. Effect of root exclusion .................................................. 260
5.3.7. Effect of legume defoliation ........................................... 268
5.4 DISCUSSION ......................................................................... 272
5.4.1. Legume species ............................................................ 272
5.4.2. Companion grass structure effects ................................. 274
5.4.3. Root exclusion effects .................................................... 275
5.4.4. Defoliation effects ......................................................... 277
5.5 CONCLUSIONS ................................................................. 279

CHAPTER 6 .................................................................................. 280

GENERAL DISCUSSION ............................................................. 280

6.1 INTRODUCTION ................................................................. 280
6.2 SITE CONTRASTS ............................................................... 282
6.3 MAGNITUDE OF RESPONSES ............................................. 284
6.4 FACTORS AFFECTING LEGUME ABUNDANCE IN HILL COUNTRY

6.4.1. Grass suppression ........................................................ 287
6.4.2. Soil-P status ............................................................... 292
6.4.3. Nitrogen application .................................................... 292
6.4.4. Defoliation management ............................................... 293
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.5</td>
<td>IMPLICATIONS AND CONSIDERATIONS</td>
<td>297</td>
</tr>
<tr>
<td>6.6</td>
<td>CONCLUSIONS</td>
<td>301</td>
</tr>
<tr>
<td></td>
<td>REFERENCES</td>
<td>304</td>
</tr>
</tbody>
</table>
Chapter 3:

Table 3.1 Summary of main effects and interaction significance. *Waipawa north aspect.*

Table 3.2 Rainfall and soil temperature (10 cm) for the experimental period at Waipawa north and south aspects, and average year.

Table 3.3 Average sward height (cm) for different main effects of cutting height, grass suppression, soil-P status and nitrogen treatments, at different dates (2000/2001). *Waipawa north aspect.*

Table 3.4 Main effects of cutting height on the standing herbage mass (kg DM/ha) of different sward components, total biomass, tiller density (tiller/m²) and white clover growing point density (g.p./m²), at different dates (2000). *Waipawa north aspect.*

Table 3.5 Main effects of cutting height on the proportion (%) of hill country sward components at different dates (2000). *Waipawa north aspect.*

Table 3.6 Main effects of autumn grass suppression on the standing herbage mass (kg DM/ha) of different sward components, tiller density (tiller/m²) and white clover growing point density (g.p./m²), at different dates (2000). *Waipawa north aspect.*

Table 3.7 Main effects of autumn grass suppression on the proportion (%) of hill country sward components at different dates (2000). *Waipawa north aspect.*

Table 3.8 Main effects of soil phosphorus status on the standing herbage mass (kg DM/ha) of different sward components, tiller density (tiller/m²) and white clover growing point density (g.p./m²), at different dates (2000). *Waipawa north aspect.*

Table 3.9 Main effects of soil phosphorus status on the proportion (%) of hill country sward components at different dates (2000). *Waipawa north aspect.*

Table 3.10 Main effects of an autumn nitrogen application on the standing herbage mass (kg DM/ha) of different sward components, tiller density (tiller/m²) and white clover growing point density (g.p./m²), at different dates (2000). *Waipawa north aspect.*

Table 3.11 Main effects of an autumn nitrogen application on the proportion (%) of hill country sward components at different dates (2000). *Waipawa north aspect.*
Table 3.12 Summary of main effects and interactions significance. *Waipawa south aspect.* ................................................................. 89

Table 3.13 Average sward height (cm) for different cutting height and grass suppression treatments, and interaction of grass suppression x soil-P status, and grass suppression x nitrogen, at different dates (2000/01). *Waipawa south aspect.* ....... 92

Table 3.14 Main effects of cutting height on the standing herbage mass (kg DM/ha) of different hill country sward components, tiller population density (tiller/m²) and white clover growing point density (g.p./m²), at different dates (2000/01). *Waipawa south aspect.* ................................................................. 94

Table 3.15 Main effects of cutting height on the proportion (%) of hill country sward components at different dates (2000/01). *Waipawa south aspect.* ......................... 95

Table 3.16 Main effects of autumn grass suppression on the standing herbage mass (kg DM/ha) of different hill country sward components, tiller population density (tiller/m²) and white clover growing point density (g.p./m²), at different dates (2000/01). *Waipawa south aspect.* ................................................................. 99

Table 3.17 Main effects of autumn grass suppression on the proportion (%) of hill country sward components at different dates (2000/01). *Waipawa south aspect.* 100

Table 3.18 Main effects of soil-P status on the standing herbage mass (kg DM/ha) of different hill country sward components, tiller population density (tiller/m²) and white clover growing point density (g.p./m²), at different dates (2000/01). *Waipawa south aspect.* ................................................................. 102

Table 3.19 Main effects of soil-P status on the proportion (%) of hill country sward components at different dates (2000/01). *Waipawa south aspect.* ......................... 103

Table 3.20 Main effects of an autumn nitrogen application on the standing herbage mass (kg DM/ha) of different hill country sward components, tiller population density (tiller/m²) and white clover growing point density (g.p./m²), at different dates (2000/01). *Waipawa south aspect.* ................................................................. 106

Table 3.21 Main effects of autumn nitrogen application on the proportion (%) of hill country sward components at different dates (2000/01). *Waipawa south aspect.* 107

Table 3.22 Summary of main effects and interaction significance. *Ballantrae.* .............. 109

Table 3.23 Rainfall and soil temperature (10 cm) for the experimental period and average year at Ballantrae and Pahiatua. ................................................................. 111

Table 3.24 Average sward height (cm) for different cutting height, grass suppression and nitrogen treatments, and the grass suppression x soil-P interaction, at different dates (2000/01). *Ballantrae.* ................................................................. 113
Table 3.25 Main effects of cutting height on the standing herbage mass (kg DM/ha) of different sward components, tiller density (tiller/m²) and white clover growing point density (g.p./m²), at different dates (2000/01). Ballantrae .................. 116

Table 3.26 Main effects of cutting height on the proportion (%) of different hill country sward components at different dates (2000/01). Ballantrae .................. 117

Table 3.27 Main effects of grass suppression on the standing herbage mass (kg DM/ha) of different sward components, tiller density (tiller/m²) and white clover growing point density (g.p./m²), at different dates (2000/01). Ballantrae .................. 120

Table 3.28 Main effects of grass suppression on the proportion (%) of hill country sward components at different dates (2000/01). Ballantrae .................. 121

Table 3.29 Main effects of soil-P status on the standing herbage mass (kg DM/ha) of different sward components, tiller density (tiller/m²) and white clover growing point density (g.p./m²), at different dates (2000/01). Ballantrae .................. 124

Table 3.30 Main effects of soil-P status on the proportion (%) of hill country sward components at different dates (2000/01). Ballantrae .................. 125

Table 3.31 Main effects of a late autumn nitrogen application on the standing herbage mass (kg DM/ha) of different sward components, tiller density (tiller/m²) and white clover growing point density (g.p./m²), at different dates (2000/01). Ballantrae. 127

Table 3.32 Main effects of a late autumn nitrogen application on the proportion (%) of hill country sward components at different dates (2000/01). Ballantrae. 128

Table 3.33 Summary of the magnitude of treatment effects on the sward legume content and white clover growing point density at the three experimental sites. .................. 129

Table 3.34 Relationship between an independent canonical variable* composed by grass related individual variables, and dependent canonical (CAN) variables** defined by legume related variables, for each of the experimental sites, as obtained from canonical correlation analysis. .................. 131

Table 3.35 Relationships between grass tiller population density and WC growing point density (GPD); WC biomass and WC content in the sward; grass biomass and GPD; GPD and WC biomass; and GPD and WC content; during the main legume-growing period in Ballantrae (Dec-Mar). .................. 134

Chapter 4:

Table 4.1 Rainfall and soil temperature (10 cm) for the experimental period at Waipawa and average year. .................. 148
Table 4.2 Summary of main effects (Management (manag), grass suppression (supp) and soil-P status (phos)), and interactions statistical significance. Waipawa. 151

Table 4.3 Effect of grazing and cutting management on average pre-defoliation grass and legume height (cm), at different dates (2001/2002). Waipawa. 152

Table 4.4 Effect of cutting and grazing management, and grass suppression on average post-grazing grass and legume height (cm), and general post-cutting sward height, at different dates (2001/2002). Waipawa. 153

Table 4.5 Effect of cutting and grazing management on standing biomass and biomass components (kg DM/ha) at different dates. Waipawa (2001-2002). 157

Table 4.6 Effect of cutting and grazing management on botanical composition of the standing biomass (% by weight) at different dates. Waipawa (2001-2002). 158

Table 4.7 Effect of grazing and cutting management on grass tiller population density (TPD; tiller/m²), white clover growing point density (GPD; g.p./m²), subterranean clover plant density (SCPD; pl/m²) at different dates, and summer SC seedling density (SC seedl./m²). Waipawa (2001/2002). 159

Table 4.8 Effect of grazing and cutting management on seasonal and total herbage mass accumulation and botanical composition of herbage accumulated (kg DM/ha). Waipawa (2001/2002). 162

Table 4.9 Effect of grazing and cutting management on the seasonal proportion of sward components (%) based on herbage accumulated. Waipawa (2001/2002). 163

Table 4.10 Effect of grass suppression on average pre-defoliation grass and legume height (cm), at different dates (2001/2002). Waipawa. 164

Table 4.11 Effect of grass suppression on standing biomass and biomass components (kg DM/ha) at different dates. Waipawa (2001-2002). 168

Table 4.12 Effect of grass suppression on botanical composition of the standing biomass (%) at different dates. Waipawa (2001-2002). 169

Table 4.13 Effect of grass suppression on grass tiller population density (TPD; tiller/m²), white clover growing point density (GPD; g.p./m²), subterranean clover plant density (SCPD; pl/m²) at different dates, and summer SC seedling density (SC seedl./m²). Waipawa (2001/2002). 171

Table 4.14 Effect of grass suppression on seasonal and total herbage mass accumulation and botanical composition of the herbage accumulated (kg DM/ha). Waipawa (2001/2002). 175

Table 4.15 Effect of grass suppression on the seasonal proportion of sward components (%) based on herbage accumulated. Waipawa (2001/2002). 176
Table 4.16 Effect of soil-P status on average pre-defoliation grass and legume height (cm), at different dates (2001/2002). Waipawa ................................................................. 179

Table 4.17 Effect of soil-P status on standing biomass and biomass components (kg DM/ha) at different dates. Waipawa (2001-2002). ................................................................. 183

Table 4.18 Effect of soil-P status on botanical composition of the standing biomass (%) at different dates. Waipawa (2001-2002). ................................................................. 184

Table 4.19 Effect of soil-P status on grass tiller population density (TPD; tiller/m²), white clover growing point density (GPD; g.p./m²), subterranean clover plant density (SCP; pl/m²) at different dates, and summer SC seedling density (SC seedl./m²). Waipawa (2001/2002). ................................................................. 185

Table 4.20 Effect of soil-P status on seasonal and total herbage mass accumulation and botanical composition of herbage accumulated (kg DM/ha). Waipawa (2001/2002). ................................................................. 189

Table 4.21 Effect of soil-P status on the seasonal proportion of sward components (%) based on herbage accumulated. Waipawa (2001/2002). ................................................................. 190

Table 4.22 Rainfall and soil temperature (10 cm) for the experimental period and average year at Ballantrae and Pahiatua ................................................................. 193

Table 4.23 Summary of main effects (management (manag), grass suppression (supp) and soil-P status (phos)), and interactions. Statistical significance. Ballantrae. ................................................................. 197

Table 4.24 Effect of grazing/cutting management, and grass suppression on average pre-defoliation grass height (cm), at different dates (2001/2002). Ballantrae. ................................................................. 198

Table 4.25 Effect of grazing and cutting management on average pre-defoliation legume height (cm), at different dates (2001/2002). Ballantrae. ................................................................. 199

Table 4.26 Management regime and grass suppression on average post-grazing grass and legume height (cm), and general sward height post-cutting at different dates (2001/2002). Ballantrae. ................................................................. 200

Table 4.27 Effect of cutting and grazing management on standing biomass and biomass composition (kg DM/ha) at different dates. Ballantrae (2001-2002). ................................................................. 202

Table 4.28 Effect of cutting and grazing management on botanical composition of the standing biomass (%) at different dates. Ballantrae (2001-2002). ................................................................. 203

Table 4.29 Effect of grazing and cutting management on grass tiller population density (TPD; tiller/m²), and white clover growing point density (GPD; g.p./m²), at different dates. Ballantrae (2001/2002). ................................................................. 204
<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.30</td>
<td>Effect of grazing and cutting management on seasonal and total herbage mass accumulation and botanical composition of herbage accumulated (kg DM/ha). Ballantrae (2001/2002).</td>
<td>206</td>
</tr>
<tr>
<td>4.31</td>
<td>Effect of grazing and cutting management on the seasonal proportion of sward components (%) based on herbage accumulated. Ballantrae (2001/2002).</td>
<td>207</td>
</tr>
<tr>
<td>4.32</td>
<td>Effect of grass suppression on average pre-grazing legume height (cm), at different dates (2001/2002). Ballantrae.</td>
<td>208</td>
</tr>
<tr>
<td>4.33</td>
<td>Effect of grass suppression on standing biomass and biomass composition (kg DM/ha) at different dates. Ballantrae (2001-2002).</td>
<td>210</td>
</tr>
<tr>
<td>4.34</td>
<td>Effect of grass suppression on botanical composition of the standing biomass (%) at different dates. Ballantrae (2001-2002).</td>
<td>211</td>
</tr>
<tr>
<td>4.35</td>
<td>Effect of grass suppression on grass tiller population density (TPD; tiller/m²), and white clover growing point density (GPD; g.p./m²), at different dates. Ballantrae (2001/2002).</td>
<td>212</td>
</tr>
<tr>
<td>4.36</td>
<td>Effect of grass suppression on seasonal and total herbage mass accumulation and botanical composition of herbage accumulated (kg DM/ha). Ballantrae (2001/2002).</td>
<td>214</td>
</tr>
<tr>
<td>4.38</td>
<td>Effect of soil-P status on average pre-defoliation grass and legume height (cm), at different dates (2001/2002). Ballantrae.</td>
<td>218</td>
</tr>
<tr>
<td>4.39</td>
<td>Effect of soil-P status on standing biomass and biomass composition (kg DM/ha) at different dates. Ballantrae (2001-2002).</td>
<td>220</td>
</tr>
<tr>
<td>4.40</td>
<td>Effect of soil-P status on botanical composition of the standing biomass (%) at different dates. Ballantrae (2001-2002).</td>
<td>221</td>
</tr>
<tr>
<td>4.41</td>
<td>Effect of soil-P status on grass tiller population density (TPD; tiller/m²), and white clover growing point density (GPD; g.p./m²), at different dates. Ballantrae (2001/2002).</td>
<td>222</td>
</tr>
<tr>
<td>4.42</td>
<td>Effect of soil-P status on seasonal and total herbage mass accumulation and botanical composition of herbage accumulated (kg DM/ha). Ballantrae (2001/2002).</td>
<td>224</td>
</tr>
<tr>
<td>4.43</td>
<td>Effect of soil-P status on the seasonal proportion of sward components (%) based on herbage accumulated. Ballantrae (2001/2002).</td>
<td>225</td>
</tr>
</tbody>
</table>
Table 4.44 Total and summer herbage accumulation and legume performance on contrasting seasons in Waipawa. ................................................................. 228

Table 4.45 Summary of the magnitude of treatment effects on the sward legume content white clover growing point density and subterranean clover plant density, during the main legume growing period, at the Waipawa (Sep-Feb) and Ballantrae sites (Nov-Mar). .................................................................................. 229

Table 4.46 Relationship between an independent canonical variable* composed by grass related individual variables, and dependent canonical (CAN) variables** defined by legume related variables, for each of the experimental sites, as obtained from canonical correlation analysis. .................................................. 233

Chapter 5:

Table 5.1 Average companion grass height (cm) for subterranean clover (SC) and white clover (WC) treatments at different dates. ...................................................... 252

Table 5.2 Legume height (cm) for subterranean clover (SC) and white clover (WC) plants under two defoliation regimes (D0 and D1), at different dates .............. 253

Table 5.3 Effect of legume species (WC or SC) on legume leaf DM (mg DM/plant), total legume shoot DM (mg DM/plant), legume leaf area (cm²/plant), red to far red (R/FR) ratio at the base of the sward, and legume root DM (mg DM/plant), at two different harvest dates (mg DM/plant). .......................................................... 254

Table 5.4 Mean grass DM (mg DM/pot), tiller density (tiller/pot) and tiller DM (mg/tiller) of swards grown along with white clover (WC) or subterranean clover (SC) plants, at two different harvest dates. .................................................. 255

Table 5.5 Average companion grass height (cm) for short (S2) and tall (T8) treatments at different dates .................................................................................. 256

Table 5.6 Effect of companion grass structure on legume height (cm), at different dates. .............................................................................................................. 256

Table 5.7 Effect of companion grass structure (Co: no grass; S2: short 2cm grass sward; T8: tall 8 cm grass sward), on average legume leaf DM (mg DM/plant), total legume shoot DM (mg DM/plant), legume leaf area (cm²/plant), number of leaves (legume), red to far red (R/FR) ratio at the base of the sward, and legume root DM (mg DM/plant), at two different harvest dates (mg DM/plant). .......................................................... 258

Table 5.8 Effect of companion grass structure (Co: no grass; S2: short 2cm grass sward; T8: tall 8 cm grass sward), on WC stolon length (cm/plant), number of WC growing points (n/plant), and number of SC branches (n/plant), at two different harvest dates .............................................................................................................. 259
Table 5.9 Mean grass DM (mg DM/pot), tiller density (tiller/pot) and tiller DM (mg/tiller) of swards with contrasting companion sward structure, at two different harvest dates.................................................................260

Table 5.10 Average companion grass height for treatments with root exclusion (R0) and no root exclusion (R1), at different dates.................................................................261

Table 5.11 Effect of root exclusion (Ro: with root exclusion, R1: no root exclusion) on legume height (cm), at different dates, and interaction root exclusion x defoliation.................................................................262

Table 5.12 Effect of root exclusion (Ro: with root exclusion, R1: no root exclusion) on average legume leaf DM (mg DM/plant), total legume shoot DM (mg DM/plant), legume leaf area (cm²/plant), number of leaves (legume), and red to far red (R/FR) ratio at the base of the sward, at two different harvest dates.................................................................263

Table 5.13 Effect of root exclusion (Ro: with root exclusion; R1: no root exclusion), on WC stolon length (cm/plant), number of WC growing points (n/plant), and number of SC branches (n/plant), at two different harvest dates.................................................................264

Table 5.14 Interaction between root exclusion and legume defoliation on average legume leaf DM (mg DM/plant), total legume shoot DM (mg DM/plant), and legume leaf area (cm²/plant), at two different harvest dates.................................................................265

Table 5.15 Interaction between root exclusion and legume defoliation on WC stolon length (cm/plant), number of WC growing points and number of SC branches, at two different harvest dates.................................................................266

Table 5.16 Interaction between companion grass structure and root exclusion on total legume shoot DM (mg DM/plant), legume leaf area (cm²/plant), and red to far red (R/FR) ratio at the base of the sward, at two different harvest dates.................................................................267

Table 5.17 Interaction between companion grass structure and root exclusion on WC stolon length (cm/plant), number of WC growing points and number of SC branches, at two different harvest dates.................................................................268

Table 5.18 Mean grass DM (mg DM/pot), tiller density (tiller/pot) and tiller DM (mg/tiller) of swards grown with or without root exclusion (Ro: with root exclusion; R1: no root exclusion) with a legume plant, at two different harvest dates.................................................................269

Table 5.19 Average companion grass height for treatments without legume defoliation (D0) or with legume defoliation (D1), at different dates.................................................................270

Table 5.20 Effect of legume defoliation (D0: no defoliation, D1: defoliated) on legume height (cm), at different dates.................................................................271
Table 5.21 Effect of legume defoliation (D0: no defoliation, D1: defoliated) on average legume leaf DM (mg DM/plant), total legume shoot DM (mg DM/plant), legume leaf area (cm²/plant), number of leaves (legume), red to far red (R/FR) ratio at the base of the sward, and root DM (mg DM/plant), at two different harvest dates (mg DM/plant).

Table 5.22 Effect of legume defoliation (D0: no defoliation, D1: defoliated), on WC stolon length (cm/plant), number of WC growing points (n/plant), and number of SC branches (n/plant), at two different harvest dates.

Table 5.23 Mean grass DM (mg DM/pot), tiller density (tiller/pot) and tiller DM (mg/tiller) of swards grown with a defoliated or un-defoliated legume plant, at two different harvest dates.

Chapter 6:

Table 6.1 Summary of field and glasshouse experiments conducted.
LIST OF FIGURES

Chapter 3:

Figure 3.1 Seasonal variation of the volumetric soil moisture of the 0-50 mm and 50-100 mm soil layers in Waipawa north aspect (2000/01) .................................................. 70

Figure 3.2 Average Seasonal variation of the volumetric soil moisture of the 0-50 mm and 50-100 mm soil layers in Waipawa south aspect (2000/01) ........................................ 91

Figure 3.3 Seasonal variation of volumetric soil moisture at the 0-50 mm and 50-100 mm layers of the soil in Ballantrae (2000/01) .......................................................... 112

Chapter 4:

Figure 4.1 Seasonal variation of the volumetric soil moisture of the 0-50 mm and 50-100 mm soil layers in Waipawa north aspect (2001/02) ........................................... 149

Figure 4.2 Seasonal variation of the TDR volumetric soil moisture (%) at different depths within the 0-40 cm layer during spring and summer, and relationship with rainfall in the previous 7, 14 and 28 days. Waipawa ........................................... 150

Figure 4.3 Vertical distribution of the root mass at different layers for grass dominated (H0) and legume dominated (H1) swards, during the active legume-growing period in Waipawa .......................................................... 177

Figure 4.4 Vertical distribution of the root density at different layers for grass dominated (H0) and legume dominated (H1) swards, during the active legume-growing period in Waipawa .......................................................... 178

Figure 4.5 Vertical distribution of soil-P at different layers under high (HP) and low (LP) soil-P status. Waipawa .......................................................... 191

Figure 4.6 Seasonal variation of soil volumetric moisture at the 0-50 mm and 50-100 mm layers of the soil in Ballantrae (2001/02) .................................................. 195

Figure 4.7 Seasonal variation of the volumetric soil moisture (%) at different depths within the 0-40 cm layer during spring and summer. Ballantrae ......................... 196

Figure 4.8 Vertical distribution of the root mass at different layers for grass dominated (H0) and legume dominated (H1) swards, during the active legume-growing period in Ballantrae .................................................. 216
Figure 4.9 Vertical distribution of the root density at different layers for grass dominated (H0) and legume dominated (H1) swards, during the active legume-growing period in Ballantrae.

Figure 4.10 Vertical distribution of soil-P at different layers under high and low soil-P status. Ballantrae.

Chapter 5:

Figure 5.2 Variation in photosynthetically active radiation (PAR; 400-700nm) in the glasshouse, during five consecutive days of measurements (5-day average values).

Figure 5.3 Above ground (shoot) yield of legume plants in swards with contrasting companion grass structure, relative to the control treatment (Co), when grown with root exclusion (R0) or without root exclusion (R1).

Figure 5.4 Leaf DM and total shoot DM yield of legume plants under defoliation (D1), relative to undefoliated plants (D0), when grown with root exclusion (R0) or without root exclusion (R1).

Chapter 6:

Figure 6.1 Seasonal variation of the available water capacity (AWC, 10 cm soil depth) in three contrasting hill country sites.

Figure 6.2 Seasonal variation of the mean soil temperature (10 cm) for three contrasting hill country sites (weekly averages).

Figure 6.3 Average total standing biomass, legume standing biomass and legume content of hill country pastures during the main legume-growing period on Waipawa north aspect in September-December 2000 (a) and September-December 2001 (b). Average responses to cutting height (h3, h7), grass suppression (H0, H1, H2), soil P status (HP, LP), nitrogen application (N0, N50), and defoliation management (C, G).

Figure 6.4 Average total standing biomass, legume standing biomass and legume content of hill country pastures during the main legume-growing period in Ballantrae in December 2000-March 2001 (a) and December 2001-March 2002 (b). Average responses to cutting height (h3, h7), grass suppression (H0, H1, H2), soil P status (HP, LP), nitrogen application (N0, N50), and defoliation management (C, G).
Figure 6.5 Legume content of swards that were not subjected to grass suppression (No), grass suppression in the current year (Same), or with grass suppression in the previous year (Prev), in Waipawa north aspect (a,b,c) and Ballantrae (d).........288

Figure 6.6 Relationship between grass content and white clover content in the sward under no grass suppression (No), grass suppression in the current year (Same), and grass suppression in the previous year (Prev), during the main legume-growing season (December-March). Ballantrae.................................................................291

Figure 6.7 Relationship between grass tiller population density (TPD) and white clover growing point density (GPD) under no grass suppression (No), grass suppression in the current year (Same), and grass suppression in the previous year (Prev), during the main legume-growing season (December-March). Ballantrae.................................................................291

Figure 6.8 Relationship between grass height and legume height (cm) during the 2001-02 growing season in Waipawa north aspect and Ballantrae.................................294

Figure 6.9 Pre- and post-grazing legume height of swards with no grass suppression (No), with grass suppression in the current year (Same) or grass suppression in the previous year (Prev) in Waipawa (a) and Ballantrae (b).................................296

Figure 6.10 Conceptual summary of factors affecting legume abundance in hill country swards.............................................................................................................298
LIST OF PLATES

Plate 3.1 General view of the experimental site at Ballantrae (summer-moist hill country) and effect of autumn herbicide application (June 2000) .........................64

Plate 3.2 Field cores during short period in the glasshouse.................................64

Plate 3.3 Grass suppression effect at the Waipawa site (north aspect). Spaces colonized by subterranean clover (September 2000) .........................................................130

Plate 3.4 Grass suppression effect at the Ballantrae site. White clover dominance in H1 plots. (March 2001) ........................................................................130

Plate 4.1 Rotational grazing with sheep at the Waipawa north aspect (Spring 2001). 143

Plate 4.2 Waipawa north aspect. Rotational grazing in summer 2002 .......................143

Plate 5.1 General view of the glasshouse experiment (March 2002) ..........................244

Plate 5.2 Insertion of clover seedlings into grass swards in pots: central hole with corer (A), insertion of seedling in exclusion tube (B); clover seedling inserted in sward (C). .................................................................244

Plate 5.3 Main treatments in glasshouse experiment. Effects of companion grass structure (A), legume defoliation (B), and root exclusion (C). .........................273